Application of Response Surface Methodology for Energy Analysis of Thin Layer Drying of Physic Nut (Jatropha Curcas)

T.B. Onifade and S.O. Jekayinfa

***Abstract*— A central composite design was used to analyze the effects of temperatures, air velocities and drying time on energy analysis of drying process of physic nuts. The data obtained from the drying kinetics were fitted into energy equations to obtain the energy utilization (EU), energy utilization ratio (EUR) and heat transfer rate due to evaporation (Q_{evap}). Response surface methodology was used to generate mathematical models for the energy responses and a quadratic polynomial equation was obtained for energy parameters by multiple regression analysis. Verification experiments confirmed the validity of the predicted model. The analysis of variance (ANOVA) depicted that the quadratic model was suitable for all responses. The predicted and experimental values of responses were in reasonable agreement with each other. An analysis of variance indicated that EU and EUR increased ($p < 0.05$) with the increasing in air temperature from 40 to 80 °C while Q_{evap} decreased ($p<0.05$) with the increasing in air temperature and velocity. The optimum value of EU was 5.468 J/s at 80 °C and 5.0 m/s while that of EUR was 0.85 obtained at a drying air of 80 °C at air velocity of 1.0 m/s. Maximum and minimum values of Q_{evap} were 17.1 J/s and 3.979 J/s while drying at 80 and 40 °C and at air velocity of 1.0 and 5.0 m/s respectively. The respective values of regression coefficient (R^2) and Adj. R^2 of the responses are; EU (0.9638, 0.9379), EUR (0.9636, 0.9376), $Q_{evap.}$ (0.9575, 0.9271). Energy was maximally utilized in the drying process of the physic nuts.**

Keywords* — Physic nut, temperature, air velocity, thin layer drying, energy analysis.

I. INTRODUCTION

Physic nut (*Jatropha curcas*) is considered to be one of the other promising energy crops (JWT, 2010) in which its seeds contain 27-40 % oil and average of 34.4% [2]. Although it produces lower yields of oil than oil palm, it has been reported that physic nut has several advantages including being able to grow on poor land (arid and marginal land), improving soil quality, requiring small amount of water, fertilizer and pesticides and providing several by-products from the production of jatropha biodiesel such as wood, fertilizer and glycerin [19]. The government has encouraged research institute and developing countries over the commercial production of this plant in order to meet up with the increasing demand for conventional fuel (Petrol and Diesel) which could not be produced up to our satisfaction [12]. A comprehensive study of energy efficiency of physic nuts dried at different temperatures and varying air velocities for bio diesel production is required, before starting a large –scale production, especially in view of the conflicting report energy efficiency of various other bio fuels done in other countries.

Practically, drying refers to application of heat and mass transfer process that involves vaporization of water in the liquid state, mixing the vapour with the drying air and removing the vapour naturally or mechanically from biomaterials [22]. Sufficient heat for vaporization of product moisture must be supplied by reducing the sensible heat of the drying air or by applying heat directly to the product by conduction, radiation, dielectric heating, freeze-drying etc. Utilizing the sensible heat content of the air is by far the most common means of drying [9]. Drying processes are very important for easy extraction of oil from seeds [18].

Natural method of drying makes use of exposure of the fresh farm produce to the sun and wind; this method is commonly used in our localities. Regular visits were paid to the local farms where physic nuts were spread on the ground and floor. Though the method is very cheap but still creates some problems. Due to erratic supply of solar energy from

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the sun, the materials are not uniformly dried; this causes deterioration and leads to product loss. At times, it may likely to rain and the farmers have to rush down to pack their produce, this means the method is stressful and causes drudgery, the observation is that some materials are under dried and yields low quality products. In other case, a farmer used a dryer which did not have temperature and fan regulator for the drying process of physic nut, this resulted to over drying of the materials. As a result, the quality and quantity of end product (bio fuel) to be obtained from such materials may be affected [18].

The drying of agricultural materials by the use of heated air has advantages on quality control, achievement of hygienic conditions, and reduction of product loss. Thin layer drying is the process of removing excess moisture from a porous media by evaporation, in which excess drying air is passed through a thin layer of the material until the equilibrium moisture content is reached [2]. This is done by uniformly spreading the material and expose to hot air [18]. The importance of a dryer is to supply the product with more heat than what available under ambient conditions, thus decreasing sufficiently the relative humidity of the drying air and increasing sufficiently the vapour pressure of the moisture held within the crop, thus increasing the moisture–carrying capacity and ensuring sufficiently low equilibrium moisture content [15].

The ability to do work is the energy contained in a substance. Forms of energy such as kinetic energy, electrical energy, and chemical Gibbs free energy are 100% recoverable as work, and therefore have an exergy equal to their energy. However, forms of energy such as radiation and thermal energy cannot be converted completely to work, and these work with the application of first law of thermodynamic, this shows the traditional method of assessing the energy dispersion of an operation [21]. An energy analysis merely provides information about the quality of energy [3] to be obtained in a substance or material. Heat energy is required for the drying process of physic nut in this research; the function of this energy is to remove excess moisture from the bio-material, if high quality product is achieved, this means energy is utilized properly and otherwise. This knowledge would be of great contribution to the determination of the quality and quantity of oil to be extracted from the dried seeds.

The work studied energy utilization in the drying process of physic nut, the effect of vtemperature and air velocity on energy responses to obtain optimum conditions that could give the desired quality products to be used for further application using the response surface methodology (RSM) has the advantage to predict responses on few sets of experimental data in which all factors are varied within a chosen range.

II. RESEARCH METHODOLOGY

The physic nuts (*Jatropha curcas)* used for the study were harvested from rural areas around Ogbomoso town (8^{o}07’ N, 4^{o}16’E) in Oyo state of Nigeria. Fresh matured fruits were selected, sorted, peeled and washed. This preparation was done to remove the stalks, leaves, stains, stones and dirty objects harvested with the fruits. The water on the physic nut was allowed to drain and then the samples were put in wire mesh baskets. The initial weight of the sample was measured using an electronic weighing balance, Mettler Toledo P.B 153 with an accuracy of 0.01g. The moisture contents of the bio-material are 84.3 % (wb) and 16.4 % (db). Each experiment was done in triplicates and average values were recorded.

A. Drying Tests

The experiment was carried out at Processing Laboratory, Department of Agricultural Engineering, Ladoke Akintola University of Technology, Nigeria. The physic nuts (5 kg) were put in three wire mesh baskets each, the weighed sample was placed on the drying trays and dried as thin layer inside a locally fabricated electric crop dryer in the Department (with good temperature and fan regulator) as shown in Fig. 1. The temperature of the dryer used was preset for 30 minutes prior to drying process and the required air velocity for drying was kept constant by turning the fan regulator. The experiments were carried out in the cabinet dryer operated at temperatures 40, 50, 60, 70 and 80 ^{o}C and varying air flow velocity of 1, 2, 3, 4 and 5 m/s. Each sample was weighed hourly using electronic balance, Mettler Toledo P.B 153 of 0.01 g accuracy and the reduction in weight was monitored until constant weight was attained. The samples were replicated three times and average reading was recorded at different temperatures and air velocity. The data obtained from drying experiments were fitted into equations of energy analysis.

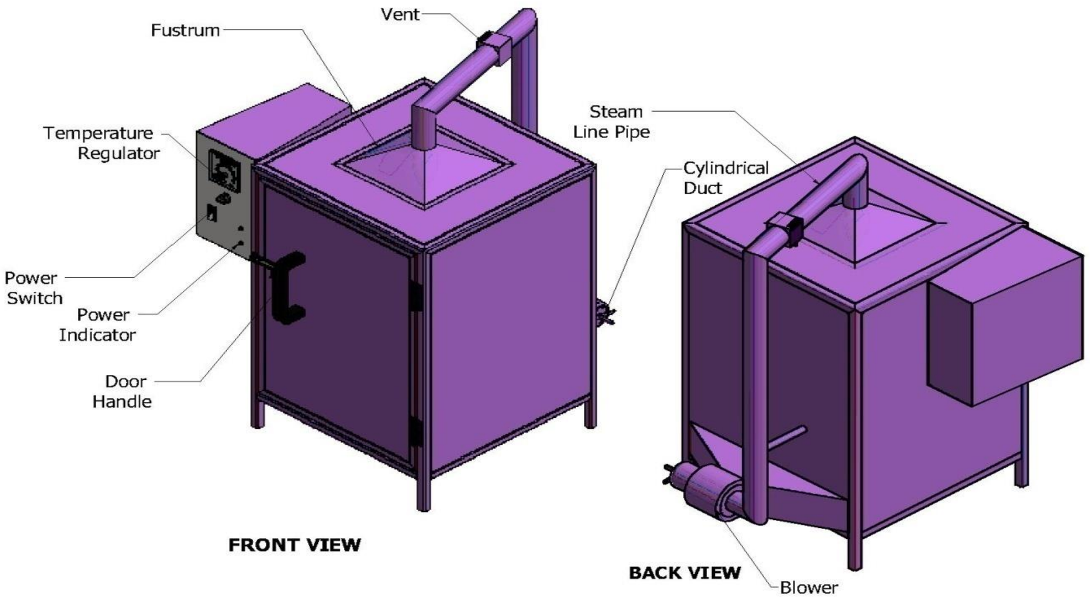

Figure 1: Pictorial view of the crop dryer

B. Energy Analysis

The energy analysis of thin layer drying process of physic nuts was performed, using the data obtained from the drying experiments at temperatures 40, 50, 60, 70 and 80 ^oC and varying air flow velocity of 1, 2, 3, 4 and 5 m/s. Thermo-hygro meter was used to measure the atmospheric temperature and relative humidity. The instrument read the outlet temperature and relative humidity values at the desired temperatures and air velocities. Psychometric chart was used to obtain different enthalpy values for the analysis.

C. Energy Utilization

The energy utilization (*EU*) was calculated by using the following equation [13]; [7]:

$$EU = m_{da}(h_{dai} - h_{dao}) \qquad (1)$$

where: $m =$ mass flow rate (kg/s),

d_a = dry air,

$h_{dai} =$ specific enthalpy of dry air inlet (kJ/kg),

h_{dao} = specific enthalpy of dry air outlet (kJ/kg)

D. Enthalpy of Drying Air

The enthalpy of drying air was determined as follows [7]:

$$h_{da} = Cp_{da}(T - T_{ref}) + h_{fg}w = (1.004 + 1.88w)(T - T_{ref}) + h_{fg}w \qquad (2)$$

where: Cp = specific heat capacity of water (J/kgs),

h_{fg} = latent heat of vaporization of water (kJ/kg),

w = humidity ratio of air (kg water kg da),

T = inlet or outlet temperature (^oC)

T_{ref} = reference or ambient temperature (^oC)

E. Energy utilization ratio (EUR)

The energy utilization ratio (*EUR*) of drying chamber was calculated using the following equation [13]:

$$EUR = \frac{m_{da}(h_{dai} - h_{dao})}{m_{da}(h_{dai} - h_{dae})} \qquad (3)$$

h_{dai} = specific enthalpy of dry air inlet

h_{dao} = specific enthalpy of dry air outlet

h_{dae} = specific enthalpy of dry air of environment

F. Heat transfer rate

The heat transfer rate due to evaporation of the dryer, (Q_{evap}) was determined as follows, [23]:

$$Q_{evap} = mwh_{fg} \quad (4)$$

Q_{evap} = heat transfer rate due to evaporation (kJ/s)

m = mass flow rate (kg/s)

w = humidity ratio of air (kg water/kg da)

h_{fg} = latent heat of vaporization of water (kJ/kg)

The mass flow rate of evaporation of the moisture removed from physic nuts within a period of time *t* were calculated by dividing the difference in fruit mass within this period of time.

III. EXPERIMENTAL DESIGN

The response surface methodology (RSM) was employed in this study. A 2^5 factorial (2 factors and 5 levels) design with three replications was used for the drying kinetics where temperatures and varying air velocities were dependent variables to obtain energy responses such as; the energy utilization (*EU*), energy utilization ratio (*EUR*) and heat transfer rate due to evaporation (Q_{evap}).

A. Statistical Analysis

Design expert 6.0.8 software was used to analyze the energy analysis parameters such as; the energy utilization (*EU)*, energy utilization ratio (*EUR*) and heat transfer rate due to evaporation (Q_{evap}). These energy responses obtained were analyzed by the response surface regression procedure using the following second-order polynomial equation:

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j=1}^{k-1} \beta_{ij} x_i x_j \quad (5)$$

Where y is the response (*EU*, *EUR* and Q_{evap}); x_i and x_j are the coded independent variables and β_0, β_i, β_{ii}, and β_{ij} are intercept, linear, quadratic and interaction constant coefficients respectively. RSM package was also used for regression analysis and analysis of variance (ANOVA). Response surfaces, normal probability and plots were developed using the fitted quadratic polynomial equation obtained from regression, holding one of the independent variables at a constant value corresponding to the stationary point and changing the other variable. The analysis curves were generated by fitting data obtained from the experiment into the above equations.

B. Results and Discussions

The range and levels of process parameters given in Table 1 were coded for high and low values of independent variables. The design matrix in Table 2 presented thirteen experimental runs in the coded units in conjunction with the experimental data and the predicted values of three response variables, the energy utilization, energy utilization ratio and heat transfer due to evaporation. The quadratic models generated by Design Expert software were used to calculate the predicted values for the responses. The experimental data, the energy utilization, energy utilization ratio and heat transfer due to evaporation were utilized to produce obtained the statistical model using multiple regression analysis method to fit the response function in accordance to Eq. 5. The corresponding model equations in term of coded variables were shown in Table 3 which presented the resulted relationships between independent variables (temperature and air velocity) and each response variable where Y_1 , Y_2 and Y_3 are energy utilization, energy utilization ratio and heat transfer due to evaporation respectively.

TABLE 1: EXPERIMENTAL RANGE AND LEVELS PROCESS VARIABLES

	Coded level and range		
Parameters	-1	0	+1
Temperature, ºC	40	60	80
Air velocity, m/s	1.0	3.0	5.0

TABLE 2: THE DESIGN MATRIX WITH EXPERIMENTAL DATA PREDICTED RESULTS

	Temp.	Air Vel.	*EU*	*(kJ/s)*	*EUR*		Q_{evap}	*(J/s)*
Run	X_i (ºC)	X_j (m/s)	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.
1	0	-1	2.24E-03	2.44E-03	0.44	0.47	5.20E-03	5.45E-03
2	-1	+1	3.06E-03	2.97E-03	0.86	0.83	0.017	0.016
3	0	0	2.91E-03	2.88E-03	0.50	0.53	3.98E-03	5.38E-03
4	-1	-1	5.47E-03	5.15E-03	0.80	0.77	7.56E-03	7.71E-03
5	0	0	2.47E-03	2.33E-03	0.47	0.43	5.19E-03	4.11 E-03
6	+1	+1	4.05E-03	4.31E-03	0.81	0.86	0.013	0.013
7	0	0	2.58E-03	2.47E-03	0.65	0.65	0.011	0.012
8	-1	0	4.09E-03	4.32E-03	0.65	0.65	6.65 E-03	5.64E-03
9	0	0	3.34E-03	3.34E-03	0.58	0.58	8.62E-03	8.62E-03
10	+1	-1	3.34E-03	3.34E-03	0.58	0.58	8.62E-03	8.62E-03
11	0	0	3.34E-03	3.34E-03	0.58	0.58	8.62E-03	8.62E-03
12	+1	0	3.34E-03	3.34E-03	0.58	0.58	8.62E-03	8.62E-03
13	0	+1	3.34E-03	3.34E-03	0.58	0.58	8.62E-03	8.62E-03

TABLE 3: THE FITTED MODEL EQUATIONS

$$Y_1 = 3.34 + 7.01A + 6.54B - 1.08A^2 + 2.78B^2 + 4.34AB$$

$$Y_2 = 0.58 + 0.15A + 1.52B + 0.032A^2 + 0.035B^2 - 0.029AB$$

$$Y_3 = 8.615 + 3.244A - 2.116B + 4.019A^2 + 6.188B^2 - 2.081AB$$

Y_1 = Exergy utilization, *EU*; Y_2= Energy utilization ratio, *EUR*; Y_3 = Heat transfer rate, Q_{evap}

Table 4 presented the analysis of variance (ANOVA) of the fitted model equations in Table 3 as evaluated by the F-test. The ANOVA reveals a significant model for energy utilization with P<0.05 at 95 % confidence level and a coefficient of determination, R^2 of 0.9638, for energy utilization ratio (*EUR*) with P-value < 0.05 at 95% confidence level and a coefficient of determination, R^2 of 0.9636, for heat transfer (Q_{evap}) with P < 0.05 value at 95% confidence level and a coefficient of determination, R^2 of 0.9575. The lack-of-fit as determined by the ANOVA (P<0.05) was not significant indicating that the response quadratic model represented the actual relationships of the experimental factors well within the ranges of experimental study. It was observed that the two factors can directly or indirectly influence *EU*, *EUR* and Q_{evap}. It is revealed that the linear and quadratic effects of temperature (A) and air velocity (B) were the primary determining factor of the responses followed by interaction effect of AB. As a single factor, the heating temperature was highly significant (p<0.05) that is, the most influential factor due to its higher F-value than that of air velocity.

From the values of "Prob>F" presented in Table 4, it can be concluded that all models representing the response variables are significant. A relatively high coefficient of determination R^2 and low coefficient of variation were obtained from the model. The resulted values are as follows; R^2 = 0.9638 and C.V. = 6.22 for Y_1, R^2 = 0.9636 and C.V. = 5.28 for Y_2 and R^2 = 0.9575and C.V. = 10.80 for Y_3. The closer the coefficient of determination to unity, with less difference between the calculated and measured values, shows the better agreement of the model and experimental data [24]. It was reported by [16] that the model adequacy can be evaluated from R^2, adjusted R^2, predicted R^2, and prediction error sum of squares (PRESS). A good model is indicated by large R^2 and a low PRESS as shown in Table 4 for each response variable. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The current study indicates ratios ratio of 19.884 for Y_1, 19.147 for Y_2 and 19.884 for Y_2 respectively which shows an adequate signal, this confirms that each model can be used to navigate the design space

TABLE 4: ANALYSIS OF VARIANCE (ANOVA) OF THE FITTED MODELS

Source	SS	DF	MS	F-value	Prob.>F
For *EU* Model	8.109	5	1.622	37.26	0.0001
A	3.929	1	3.929	90.27	0.0001
B	3.420	1	3.420	78.58	0.0001
A^2	8.039	1	8.039	0.018	0.8957
B^2	5.357	1	5.357	0.121	0.7360
AB	7.534	1	7.534	17.31	0.0042
Residual	3.046	7	4.352		
Lackof fit	3.046	3	1.015		
Pure error	0.00	4	0.000		
Cor total	2.41	12			
R^2 = 0.9638; Adj R^2 = 0.9379; Pred. R^2 = 0.7425; Adeq. Prec. = 19.884; C.V = 6.22; PRESS = 0.0021					
For *EUR* Model	0.204	5	0.040	37.08	0.0001
A	0.180	1	0.811	169.21	0.0001
B	1.850	1	1.850	0.017	0.8992
A^2	7.213	1	7.213	6.72	0.0358
B^2	8.522	1	8.522	7.94	0.0258
AB	3.422	1	3.422	3.19	0.1173
Residual	7.510	7	1.073		
Lackof fit	7.510	3	2.503		
Pure error	0.000	4	0.000		
Cor total	0.210	12			
R^2 = 0.9636; Adj R^2 = 0.9376; Pred. R^2 = 0.7413; Adeq. Prec. = 19.147;C.V = 5.28; PRESS = 0.053					
For Q_{evap} Model	1.374	5	2.747	37.26	0.0001
A	8.421	1	8.421	90.27	0.0001
B	3.581	1	3.581	78.58	0.0004
A^2	1.124	1	1.124	0.018	0.9128
B^2	2.663	1	2.663	0.121	0.9865
AB	1.732	1	1.732	17.32	0.0029
Residual	6.103	7	8.718		
Lack of fit	6.103	3	2.034		
Pure error	0.000	4	0.000		
Cor Total	1.435	12			
R^2 = 0.9575; Adj R^2 =0.9271; Pred. R^2 = 0.6975; Adeq. Prec. = 18.910; C.V =10.80; PRESS = 0.0043					

The effect of two factors (temperature and air velocity) on *EU*, *EUR* and Q_{evap} was found out using three dimensional and normal probability plots. The response surface plots for the *EU*, *EUR* and Q_{evap} as shown in Figs. 5-7 depict the interaction between the drying temperature and air velocity from the response model. The normal probability plot in Fig. 5a-7a show the distribution of residual value defined as the difference between the predicted and experimental data for all response variables of energy utilization; temperatures and air velocity are forming a straight line.

It was observed that *EU* and *EUR* increased with increasing temperature and fairly constant with increase in air velocity, but Q_{evap} decreased with increase in temperature. This indicates that effects of air velocity on EU and EUR were lower than those by air temperature. It is clearly seen that the residual values are normally distributed on both sides of the line indicating that the experimental data are in excellent agreement with the outstanding adequacy of the proposed quadratic model to represent the variable responses of energy utilization, energy utilization ratio and heat transfer in the range of temperature and air velocity: 40-80 °C and 1.0-5.0 m/s respectively. Figures 5b-7b show the 3D response surface of the interaction between the two variables; temperature and air velocity, both factors have positive effect on *EU*, *EUR* and Q_{evap} as presented in Table 3. It is also observed from 3D plot that *EU* and *EUR* increased while Q_{evap} decreased with increasing temperature and slightly with increase in air velocity.

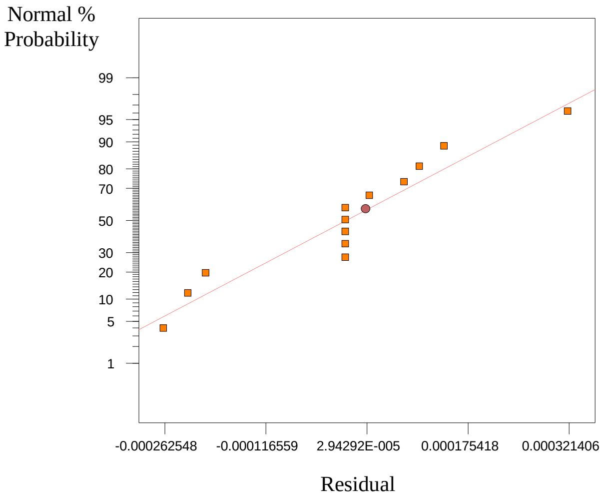

Figure 5a: Normal probability plots for energy utilization

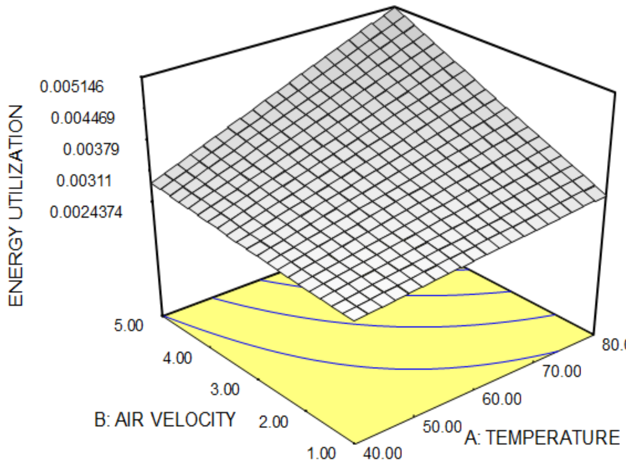

Figure 5b: Response surface plots for energy utilization

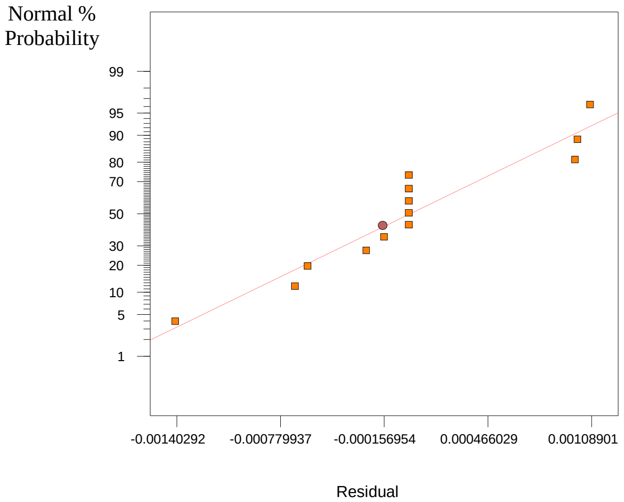

Figure 7a: Normal probability plot for Q_{evap}

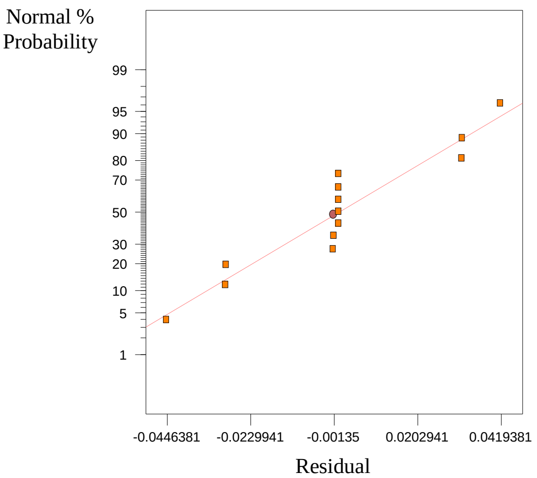

Figure 6a: Normal probability energy utilization ratio

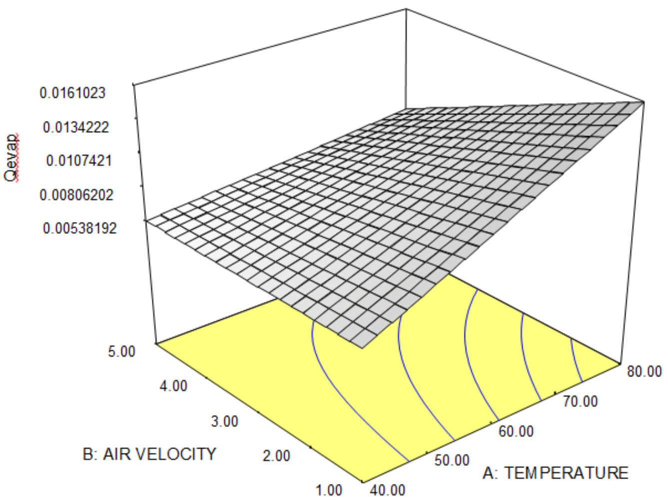

Figure 7b: Response surface plots for Q_{evap}

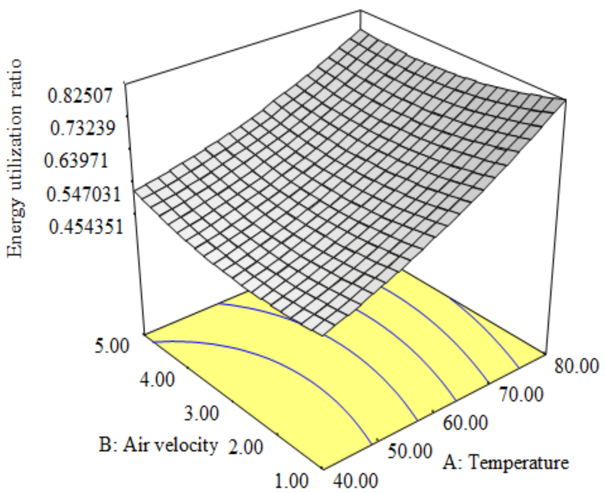

Figure 6b: Response surface plots for energy utilization ratio

The results of energy analysis of thin layer drying of physic nut are presented in Figures 2-4. It was observed that temperature and air velocity affected the drying rate of physic nut.

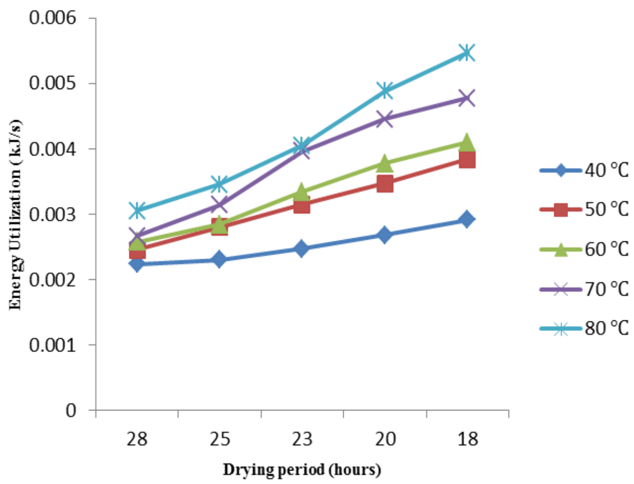

Figure 2: Energy utilization in physic nut drying process

Fig. 2 shows the variation of energy utilization (*EU*) as a function of time. As shown in this figure, the energy utilization decreased with increasing drying time. Its maximum value occurs at the beginning of drying process. This is as result of high moisture of the wet samples which reduces toward the end of the process. Increasing inlet temperature and air velocity raised the energy utilization and air inlet enthalpy, thereby, increasing mass and heat transfer to translate higher energy utilization. The maximum and minimum value of 0.00549 kJ/s and 0.00224 kJ/s were obtained for *EU* at 80 ºC, 5.0 m/s and 40 ºC, 1.0 m/s respectively. This indicated that the heat energy provided by the electric heating element in the dryer was capable of yielding materials of low moisture content which resulted to high quality. This implies the significant effect of temperature and air velocity on *EU* at 95 % confidence level. This finding was similar to those reported for drying pomegranate arils in the control treatment [14], drying of coroba slices [7] and convention slices of red pepper [4] and silicon drying of potato and pumpkin slices [5].

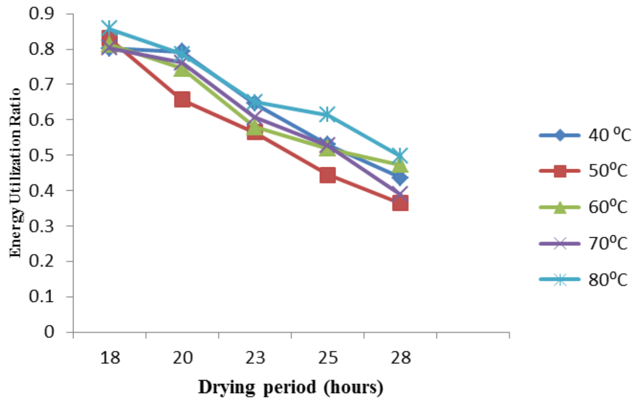

Figure 3: Energy utilization ratio in the drying process of physic nut

Fig. 3 demonstrates the trend of energy utilization ratio in the drying of physic nut. This indicates the variation of energy utilization as a function of time at constant temperature and various air velocities. It is observed that *EUR* decrease with increasing drying time. The maximum value of *EUR* obtained was 0.85 for drying at temperature of 80 ºC with air velocity of 1.0 m/s. The minimum value of 0.36 was obtained at 40 ºC with air velocity of 5.0 m/s. This indicates that the energy provided in the drying chamber is equal to the quality of the product obtained. This shows that effect of temperature and air velocity on EUR is significant at 95 % confidence level. These results resemble those reported by [8] for drying pumpkin slices in silicon dryer and [17] for drying carrot cubes. This is not similar in the drying process of mulberry in a forced solar dryer where EUR decreased with increasing temperatures [1].

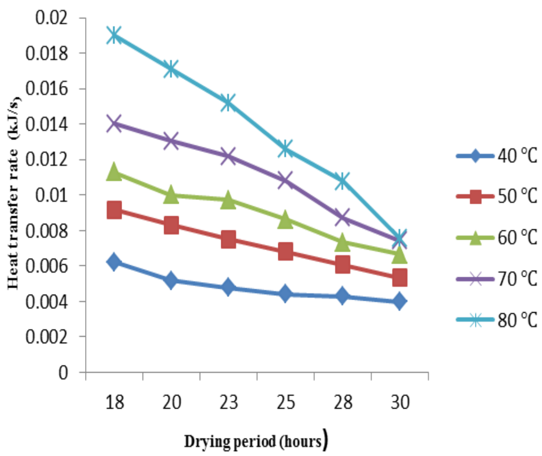

Figure 4: Heat transfer due to evaporation as a function of time in the drying process of physic nut

Fig. 4 illustrates the trend of heat transfer rate due to evaporation in the drying process of physic nut. Q_{evap} increased with the increasing in air temperature and velocity but decreased with drying time. Maximum and minimum values of Q_{evap} were 17.1 J/s and 3.979 J/s while drying at 80 and 40 ºC and at air velocity of 1.0 and 5.0 m/s respectively. The Q_{evap} decreases as the surface moisture evaporates until the end of the drying process. This is because moisture on the material surface evaporates quickly at higher temperature and making the force of attraction within the material and its wall weakens. Higher temperature sufficiently increases the vapour pressure of the moisture held within the crop and decreases the relative humidity in the dryer, and ensures sufficiently low equilibrium moisture content. This result is in accordance with the findings of [7] in the thin layer drying of coroba fruit slices; but reverse is the case in the findings of [11], the value of Q_{evap} in the heat pump tumbler dryer was investigated to be very low. This may be due to smaller drying space (medium) which may affect the escape of moisture.

IV. CONCULSION

The energy analysis of thin layer drying of physic had been established. From the study accomplished, the following conclusion are drawn; energy utilization and energy utilization ratio increased as temperature and air velocity increased, but heat transfer rate due to evaporation decreased with increased drying conditions. Hence, heat energy supplied by the crop dryer was utilized to produce high quality products. The energy responses obtained by RSM indicated that experimented and predicted values are in reasonable agreement. The products obtained can be recommended for further processing (bio-oil and biofuel production).

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APPENDIX

NOMENCLATURE

Cp specific heat (kJ/kg °C)

EU energy utilization (kJ/s)

EUR energy utilization ratio (*dimensionless*)

h specific enthalpy (kJ/kg)

hfg latent heat of vaporization of water (kJ/kg)

m mass flow rate (kg/s)

p significant level

$Qevap$ heat transfer rate due to evaporation (kJ/s)

T temperature (℃)

w humidity ratio of air (kg water/kg da)

R^2 coefficient of regression (*dimensionless*)

Adj. R^2 Adjusted coefficient of regression (*dimensionless*)

Pred. R^2 Predicted coefficient of regression (*dimensionless*)

Adeq. Pre Adequate precision (*dimensionless*)

C.V. coefficient of variation

SUBSCRIPTS

da dry air

e environment

i inlet

o outlet

ref refers to characteristics value